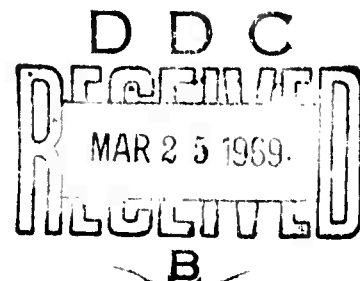


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## Table of Contents

	Page
Abstract.....	1
I. Introduction.....	3
II. Earth Structure: Elastic and Anelastic Properties...,.....	3
III. Seismic Waves: Theoretical Studies .....	11
IV. Seismic Sources: Theoretical and Observational Studies.....	15
V. Instrumental Development and Automated Data Processing.....	20
VI. Previous Technical Reports in this Series.....	21

### Abstract

The structure of the crust and upper mantle in the Western United States has been intensively studied by refraction and reflection techniques. Strong lateral variations have been found which correlate well with gravity, heat flow, P-delay, and other geophysical data. Methods have been developed to handle lateral variations both for body wave and surface wave studies. Near vertical reflections and precursors to the phase P'P' have been used to study discontinuities in the upper mantle. There are at least 6 reflectors or discontinuities in the upper mantle below 100 km. Most of the lateral changes in the upper mantle occur in the vicinity of the low-velocity zone.

A method has been developed for analyzing high pressure shock wave data in order to make direct comparisons with seismic data. The lower mantle is clearly enriched in iron compared to the upper mantle.

The low-velocity zone has been determined to be caused by partial melting. One or two per cent melt is adequate to explain the low-velocities and high attenuation. Compressional wave spectral data have been used to verify the highly attenuating nature of the low-velocity zone. The S/P amplitude method has been shown to be a powerful diagnostic of the state of the upper mantle.

Free oscillation data have been inverted to obtain continental and oceanic Earth models. A low-density zone in the upper mantle has been found from these studies, but the lid of the low-velocity zone has a much higher density than previously suspected.

Theoretical work for wave propagation in inhomogeneous media has provided a number of results in diffraction theory which are important in determining the nature of the Earth's core mantle boundary. Generalizations of the preliminary theory indicate that a weakly inhomogeneous mantle bounded by a fluid core can also be treated successfully. A number of approximate theories for body wave propagation have been developed, and their extension and application to body wave transmission in an inhomogeneous Earth promises to provide a much better interpretation of amplitude data than is afforded by simple ray theory yet retain much of the simplicity of ray theory analysis. All of these results will enable us to obtain a much more detailed determination of the Earth's anelastic properties as well as its elastic properties. The effect of lateral inhomogeneities on torsional free oscillation data has been studied theoretically using a perturbation theory approach. Rather large effects are predicted at the shorter periods for realistic lateral inhomogeneities, as expected, but it is found that the effects are significant for all periods. This theory indicates the nature of the averaging process implicit for the mean Earth models determined under the assumption of only radial inhomogeneity in the Earth.

Theoretical and observational work on seismic sources has led to models of earthquakes which satisfy the observations in great detail. Dislocation models have been used to determine stress drop, seismic moment, and fault dimensions. Determinations of stress drop for a number of small earthquakes gives spatial groups for which the stress drop was 7, 30, and 100 bars, respectively. A specialization of a tectonic relaxation source model has been used to explain the anomalous radiation from underground explosions as stress release from the region around the shatter zone. The method allows the determination of prestress in the region of the explosion, among other source parameters, and a prestress of approximately 70 bars was obtained for the Nevada Test Site.

Studies of the static strains and tilts using appropriate source models in media with decoupling or soft zones indicate that the observations of large tilts accompanying some earthquakes may be the result of block decoupling phenomena in the western part of the Continent. However, the results are not conclusive and a number of other possibilities exist so that further work is required.

## I. Introduction

The research accomplishments under this grant have been established in a series of technical papers listed at the end of this report. The content of these papers has been summarized in previous Quarterly Reports. The present report is a review of the work accomplished for the period 1 November 1967 to 31 October 1968 and is concerned with research in the following areas:

1. Structure of the earth; elastic and anelastic properties, composition and thermodynamic state
2. Theoretical studies of seismic wave propagation
3. Theoretical and observational studies of seismic sources
4. Instrumental development and automated data processing

In the following sections we briefly summarize accomplishments and work initiated in these areas during the past year. These summaries are followed by abstracts of papers submitted or published during this period. Titles of papers presented at various scientific meetings and to be submitted for publication are also included.

## II. Earth Structure: Elastic and Anelastic Properties

The principal objective of research in this area has been to determine seismic velocities, density and anelastic dissipation as functions of depth in the earth using seismic techniques. An essential part of our work has therefore involved the analysis and inversion of free oscillation data to yield mean or average earth models. Coupled with this effort has been the development of various inversion methods, the latter are summarized in the next section. In the course of this work it was recognized that the inherent lack of uniqueness of the inversion problem required constraints based on independent information pertinent to density and elastic properties of the earth in order to limit the derived models to physically meaningful cases. These constraints were obtained from information on the earth's mass or mean density and moment of inertia and from high pressure-temperature measurements of mechanical properties. In addition, the free oscillation data were combined with body wave data and/or velocity models obtained from body wave data. The resulting mean earth models are considered to be at or near the meaningful limit for an average earth model. That is, in view of the irreducible scatter in the data introduced primarily by lateral variations in the earth's mantle as well as by uncertainties of observation, much more refinement of these models using the present theory appears unrealistic in view of the uncertainty of the physical interpretation to be attached to any finer details of these average earth models.

The inversion method used is a pseudo-inverse matrix method which is a powerful and efficient method of inverting many kinds of geophysical data. The important common features of successful models are the high density at the top of the mantle ( $3.4 - 3.6 \text{ g/cm}^3$ ), the low-density of the mantle between about 100 and 300 km ( $3.3 \text{ g/cm}^3$  or less) and the high Poisson's ratio of the inner core (0.45 or greater). The mechanical instability of the upper mantle has important bearing on tectonic processes. The chemical discontinuity in the upper mantle, which is superimposed on the phase discontinuities, has been verified.

In view of preliminary inferences of strong lateral variations in the mantle as well as in the crust of the earth from reconnaissance studies, strong emphasis has been placed on methods of determining regional structure using both surface wave and body wave methods. Use of travel times, amplitudes and body wave phase velocity methods have been especially powerful in the resolution of the fine structure of the earth's mantle on a regional basis. The body wave methods have generally made use of the mean earth structures obtained from free oscillation data as well as the average earth models obtained from surface wave studies for "super-provinces" of the earth, in particular, the regions ordinarily designated as shield, tectonic, and oceanic. These average earth models are used as starting solutions for the iterative procedures employed to invert body wave data and taken together, the seismic studies give mean earth models plus high resolution models appropriate to specific 'mantle provinces' for the earth. Hence, we have obtained a progressively finer resolution of earth structure, which shows quantitatively the nature and extent of lateral variations as well as radial variations. As one consequence of this work, travel time and amplitude variations for first and later arrivals have been explained in terms of regional mantle and crust structure and such results and data are of great practical importance for the location and detection of seismic events.

Stimulated by the seismic results, which are described in detail by the abstracts below, several new but related projects were undertaken. Basically these investigations involve the integration of the seismic results with other geophysical information including high pressure-temperature solid state and shock wave data. Hence, use of the seismic data along with an equation of state obtained from solid state and shock wave data has enabled us to obtain information on the material composition and its phase. In particular, transition zones marked by high velocity gradients in the upper mantle can be shown to correlate with known phase transitions of mantle silicates. Integration of the seismic results with observations of gravity, heat flow, and electrical conductivity data has also allowed us to improve our knowledge of the nature of lateral variations in the crust and mantle. This is particularly useful in determining structure in the transitional regions between major crust-mantle provinces where resolution of the complicated structure by seismic methods alone is difficult. Most importantly we have shown a consistency among the geophysical observations when interpreted in this manner

and the data has provided us with a rather detailed picture of the upper mantle and crust over much of the continent, with quantitative knowledge of the temperature, density, elastic and anelastic properties, and the phase state of the material. These results have in turn led us to investigate mechanisms of crust-mantle evolution

Abstracts of Papers Submitted for Publication:

Anderson, Don L., "Chemical Inhomogeneity of the Mantle," Earth and Planetary Science Letters, (in press).

The major portion of the increase in density and elastic properties through the transition region of the upper mantle can be attributed to phase changes. However, the density increase in the Earth is slightly greater and the observed increase of the seismic velocities is slightly less than predicted on the basis of phase changes alone. The data can be reconciled with an increase in the mean atomic weight of about 1.5 to 1.6 units. This implies an increase in the FeO/MgO ratio of about 0.17 to 0.18, the lower mantle being more iron rich than the upper mantle.

Anderson, Don L., and Hiroo Kanamori, "Shock-Wave Equations of State for Rocks and Minerals," Journal of Geophysical Research, 73, 6477-6502, 1968.

A method is proposed for estimating the zero-pressure parameters of the high-pressure high-temperature phases formed by intense shock loading of rocks and minerals. The method involves an empirical relationship between the zero-pressure mean molar volume and the slope at the base of the P-V curve. Equations of state are fitted to shock-wave data for eighteen rocks and minerals. Most of the materials collapsed to a denser phase or assemblage of phases when shocked to sufficiently high pressure. If a phase change occurs, parameters of the high-pressure phase are found for a range of  $\rho_0$  from both the raw Hugoniot and an estimated metastable Hugoniot. The polymorphic transitions involve a considerable reduction in volume, ranging from 33 to 49% for feldspar and quartz-rich rocks such as albitite, anorthosite, and granite, 20% for such basic rocks as diabase and dunite, and about 12% for some dense already closely packed minerals such as spinel, hematite, and magnetite. The parameter  $(dK/dP)_0$ , which is related to the Gruneisen ratio, is found to decrease across phase changes and upon iron substitution.

Anderson, Don L., and David G. Harkrider, "Universal Dispersion Tables, II. Variational Parameters for First Four Love Modes for an Oceanic and A Continental Earth Model," Bull. Seismol. Soc. Am., 58, 5, 1407-1499, 1968.

The universal dispersion theory, presented in Part I, is extended to allow computation of group velocity and amplitude partial derivatives. Tables giving the effect of a change in any parameter on phase velocity, group velocity and amplitude are given for two earth models, one oceanic and one continental shield. Tables are given for the fundamental and first three higher Love modes.

These tables make it possible to compute dispersion parameters for the first four Love modes for any realistic earth model or to invert observations to an earth model. Attenuation of Love waves for an arbitrary distribution of  $Q$  versus depth can also be computed by using techniques previously described.

Anderson, Don L., and Bruce R. Julian, "Shear Velocities and Elastic Parameters of the Mantle," J. Geophys. Res. (in press).

The recent shear wave data of Ibrahim and Nuttli (1967) and Doyle and Hales (1967) is reinterpreted to yield a shear-velocity structure that is compatible with Johnson's (1967) compressional-velocity structure. The elastic parameters  $\phi$ ,  $K/\mu$  and  $\sigma$  are calculated as a function of depth. All three parameters increase with depth in the homogeneous regions of the mantle but only  $\phi$  increases through the transition regions. Poisson's ratio is apparently less for the close-packed deeper mantle phases than it is for the normal phases of the upper mantle.

Anderson, Don L., and Robert L. Kovach, "Universal Dispersion Tables, III. Free Oscillation Variational Parameters," Bull. Seismol. Soc. Am. (in press).

The effect of a small change in any parameter of a realistic Earth model on the periods of free oscillation is computed for both spheroidal and torsional modes. The normalized partial derivatives, or variational parameters, are given as a function of order number and depth in the Earth. For a given mode it can immediately be seen which parameters and which regions of the Earth are controlling the period of free oscillation. Except for  $S_0$  and its overtones the low-order free oscillations are relatively insensitive to properties of the core. The shear velocity of the mantle is the dominant parameter controlling the periods of free oscillation and density can be determined from free oscillation data only if the shear velocity is known very accurately. Once the velocity structure is well known free oscillation data can be used to modify the average density of the upper mantle. The mass and moment of inertia are then the main constraints on how the mass must be redistributed in the lower mantle and core.



Anderson, Don L., and Charles Sammis, "The Low Velocity Zone," Proceedings of the Pan-American Symposium, 1968.

The low velocity zone in tectonic and oceanic regions is too pronounced to be the effect of high temperature gradients alone. Partial melting is consistent with the low velocity, low  $Q$  and abrupt boundaries of this region of the upper mantle and is also consistent with measured heat flow values. The inferred low melting temperatures seem to indicate that the water pressure is sufficiently high to lower the solidus about  $200^{\circ}\text{C}$  to  $400^{\circ}\text{C}$  below laboratory determinations of the melting point of anhydrous silicates.

The mechanical instability of a partially molten layer in the upper mantle is probably an important source of tectonic energy. The top of the low-velocity zone can be considered a self-lubricated surface upon which the top of the mantle and the crust can slide with very little friction. Lateral motion of the crust and upper mantle away from oceanic rises is counterbalanced by the flow of molten material in the low-velocity layer toward the rise where it eventually emerges as new crust. If this lateral flow of molten material is not as efficient as the upward removal of magma, then regions of extrusion, such as oceanic rises, will migrate.

Archambeau, C. B., E. A. Flinn and D. G. Lambert, "Fine Structure of the Upper Mantle," J. Geophys. Res. (in press).

The lateral and radial variations of upper mantle elastic velocities are required in considerable detail for an understanding of the physical state of the material in the mantle. This same information is required for any quantitative discussion of tectonics and in general for models of dynamical processes associated with the evolution of the planet. In this study we use the spectral amplitudes and travel times of seismic body waves to determine mantle velocity structures appropriate to distinct structural provinces within the western continental United States. In addition to basic amplitude and time data, travel time delays and  $P_n$  velocity data from other studies are used as constraints in the systematic inversion of the data for mantle structure. The regional structures for the upper mantle determined in this manner, show collectively, rather sharp zones of transition (high velocity gradients) near 150 km, 400 km, 650 km and possibly near 1000 km. Comparatively, the regional structures indicate strong lateral variations in the upper mantle structure down to 150 km and possibly as deep as 200 km. The structures appropriate to the Rocky Mountain and Colorado plateau physiographic provinces show low velocity zones capped by high velocity lid zones, with variability in both the lid and low velocity zone properties from province to province, and within these provinces to a much lesser degree. The mantle properties obtained for the Basin and Range contrast sharply with the plateau and mountain structures, with the lid zone being very thin or absent and abnormally low velocities extending from, or very near the base of a thin crust to 150 km. The velocity determinations are coupled with estimates of the variation of the intrinsic dissipation function ( $Q$ ) as a function of depth and frequency. These results show a

pronounced low Q zone corresponding to the average low velocity zone depth range for the velocity models. The data suggests a frequency dependent Q, with Q increasing with frequency. In total the results of the study strongly suggest phase transitions in the mantle, including a partially melted region corresponding to the low velocity zone, the latter being highly variable in its properties over the region studied and strongly correlated with tectonic activity.

Johnson, Lane R., "Array Measurements of P Velocities in the Lower Mantle," Bull. Seismol. Soc. Am. (in press).

The extended array at the Monto Forest Seismological Observatory in central Arizona has been used to measure  $dT/d\Delta$  of direct P waves from 212 earthquakes in the distance range between 30 and 100°, and these data have been inverted to obtain a velocity model for the lower mantle. Travel times calculated for this model are in good agreement with empirical travel times. The  $dT/d\Delta$  data from different azimuths and from different focal depths are all in reasonably good agreement with the exception of anomalously large values from earthquakes on the mid-Atlantic ridge. The effect of the core on the measured values of  $dT/d\Delta$  at distances greater than 90° is shown to be significant, and a correction is made for this effect. A curve fit to the  $dT/d\Delta$  data contains anomalous regions near the epicentral distances of 34.5, 40.5, 49.5, 59.5, 70.5, and 81.5° which may correspond to increased velocity gradients near the depths of 830, 1000, 1230, 1540, 1910, and 2370 km. PcP times were used to estimate a core radius of 3481 km.

Jackson, David D., and Don L. Anderson, "Physical Mechanisms of Seismic Wave Attenuation," Rev. Geophys. (in press).

The theoretical and experimental evidence concerning mechanisms likely to be responsible for the attenuation of seismic waves are reviewed. Intergranular thermoelastic relaxation, atomic diffusion, and dislocation mechanisms may not be ruled out as significant causes of seismic attenuation, but the most effective mechanisms seem to be associated with partial melting, grain boundary relaxation, and a poorly understood mechanism, called "high temperature background internal friction," which obeys a law of the form

$$Q^{-1} = (A/f) \exp (-H^*/RT).$$

Here  $Q^{-1}$  is a dimensionless measure of anelasticity,  $f$  is the frequency,  $T$  is the absolute temperature, and  $A$ ,  $H^*$ , and  $R$  are constants for a material of uniform composition and grain size. Many of the mechanisms considered here exhibit a strongly frequency dependent  $Q^{-1}$ . However, in a material as complex as a rock there is unlikely to be a single discrete relaxation time or activation energy, or a single "typical"

grain size. The observed  $Q^{-1}$  is likely to result from a superposition of several mechanisms and involve a spectrum of parameters leading to weaker frequency dependence than is predicted from a single simple mechanism. The seismic data cannot at present resolve the question of whether or not  $Q^{-1}$  has an intrinsic frequency dependence. The extent and the limitations of the available seismic data are discussed. Experimental data on the attenuation of oxides is summarized, with emphasis on measurements at high temperature and low frequency.

McGinley, John R., and Don L. Anderson, "Relative Amplitudes of P and S Waves as a Mantle Reconnaissance Tool," Bull. Seismol. Soc. Am. (in press).

The unified magnitude, the ratio of the amplitudes of S to P waves, and travel time residuals were compiled from published data for the five Seismological Observatories, TFO, UBC, BMO, WMO and CBO. Using one of the stations as a reference, a relative measure of the above quantities was calculated for each of the other stations for each of a number of earthquakes. The stations in the Basin and Range Province are consistent with a markedly higher attenuation of P waves and a high attenuation of S relative to P when compared to the other stations. This latter observation indicates a high Poisson's ratio in the mantle under the Basin and Range. The delay times to these stations are also consistent with the high Poisson's ratio and with a low velocity upper mantle. The ratio of the amplitudes of long period S waves to short period P waves varies by a factor of 4 among these stations.

The station in eastern Oregon has a high S/P amplitude ratio compared to other stations and a travel time residual that is comparable to the observatories in the mid-continent. This may be another example of a seismic "window" into the upper mantle that is generated by underthrusting of the oceanic lithosphere.

Wu, Francis T., "The Inverse Problem of Magnetotelluric Sounding," Geophysics (in press).

Based on the model of a flat layered earth, a non-linear least square method is used to invert magnetotelluric sounding curves to obtain the layer resistivities and thicknesses. Partial derivatives of the apparent resistivity with respect to layer parameters are displayed to show the manner in which the layer parameters are contributing to the apparent resistivities. Uniqueness of the inversion is not guaranteed, but when the partial derivatives are linearly independent and the relative magnitudes of the layer resistivities of the initial guess are not too far from the correct ones, the convergence of the method to the correct values seems to be ensured.

Titles of papers presented at meetings:

Anderson, Don L., and M. Smith, "Mathematical and Physical Inversion of Gross Earth Geophysical Data," Trans. Am. Geophys. U., 49, 1, March 1968.

Archambeau, C. B., R. Roy, D. D. Blackwell, D. L. Anderson, L. Johnson, and B. Julian, "A Geophysical Study of Continental Structure," Trans. Am. Geophys. U., 49, 1, March 1968.

Julian, B. R., R. F. Roy, and D. D. Blackwell, "Travel Times from the Nuclear Explosion Gasbuggy in the Colorado Plateau and Basin and Range Provinces," Trans. Am. Geophys. U., 49, 1, March 1968.

Julian, B., "Computer Inversion of Body Wave Data," Trans. Am. Geophys. U., 49, 4, December 1968.

Whitcomb, James, and Don L. Anderson, "Reflections from Upper Mantle Discontinuities," Trans. Am. Geophys. U., 49, 4, December 1968.

### III. Seismic Waves: Theoretical Studies

These investigations have been in two principle areas, asymptotic wave theory and theory connected with free oscillations. In the latter, we have considered improved methods of inversion and questions of uniqueness. In addition, perturbations in the earth's free oscillations due to lateral variations have been considered.

In view of the observations of rather strong lateral changes in the earth's upper mantle and with the possibility of similar changes, although probably of much less magnitude in the lower mantle, we have investigated the effects of simple lateral inhomogeneities as perturbations in an otherwise radially inhomogeneous earth. The development of the theory has been carried out for the torsional oscillations of the earth and preliminary calculations show that the effect of observed lateral variations on free oscillation spectra is quite significant. That is, the effects are such that different points of observation on the earth's surface will give different natural periods of oscillation for the same mode. For modes above  $\ell = 20$  the period shift relative to the periods of an ideal radially inhomogeneous earth are of the order of, or larger than, the accuracy of measurement. This shows quantitatively what the nature of the scatter will be, and of what magnitude. It also predicts the nature of the dependence of the period measured on the source and when compared to the usual theory which assumes only radial inhomogeneity, the nature of averaging of lateral variations for a mean earth structure.

Problems of diffraction at the earth's core and other sharp discontinuities in the earth have also been treated. These have been handled in the general area of asymptotic wave theory although the approximations, when made, have not always been asymptotic. Thus, basic results on wave diffraction of plane waves at a cylindrical cavity have been obtained, and in addition more general results of an approximate form have been obtained for a spherical fluid core in an inhomogeneous mantle. The effects of P-SV coupling in waves propagating in a continuously variable radially inhomogeneous medium have been investigated in great detail. This work will give much more precise amplitude relations for use in structural studies, particularly for anelastic studies and will also be highly useful in reducing amplitude data for detailed source studies.

Inverse problems in science generally as well as in geophysics are of great importance since inversion theory not only tells us how to interpret data systematically but in addition whether the inverse obtained is unique and the uncertainty to be associated with it. We have developed a number of inversion methods for dealing specifically with seismic data in the past. This work has continued and inversion methods for body wave as well as surface wave and free oscillation data have been developed and are currently being applied. Some of these applications are discussed in Part I of this report. More

sophisticated inversion procedures have been developed during the past year and are the basis for automated inversion of the data as well as a general parameterization of geophysical observations.

Abstracts of Papers Submitted for Publication:

McGinley, John R., Jr., "A Comparison of Observed Permanent Tilts and Strains due to Earthquakes with those Calculated from Displacement Dislocations in Elastic Earth Models," Ph.D. Thesis, California Institute of Technology, Pasadena, 1969.

A perturbation procedure is developed for calculating the effects of lateral changes in elastic constants on the earth's free oscillations. The procedure is applied to obtain expressions for the effect of some simple inhomogeneity geometries on the torsional free oscillations.

Smith, Martin L., and Joel N. Franklin, "A Geophysical Application of Generalized Inverse Theory," J. Geophys. Res. (in press).

Generalized inverse theory provides techniques for solving systems of linear equations of arbitrary size and degeneracy; i.e., the number of equations may be greater than, the same as, or less than the number of unknowns, and the rank of the matrix expressing the equations need not be the same as its smallest dimension. The theory is direct and is well-developed in the mathematical literature. We wish to briefly discuss this theory and its application to a special case of geophysical inverse problems. As will be pointed out, the theory provides results of computational utility.

Teng, Ta-Liang, and Paul G. Richards, "Diffracted P, SV, and SH Waves and Their Shadow Boundary Shifts," J. Geophys. Res., March 1969.

Diffraction of plane body waves caused by a cylindrical cavity in an otherwise homogeneous, elastic, and infinite medium has been studied for wave periods up to 100 seconds. Poisson's summation formula is used in formulating the theory, followed by an asymptotic expansion to isolate the diffracted energy that arrives in the correct time window. A numerical study is also conducted to examine in detail the behavior of the diffracted amplitudes near the shadow boundary. It is found that the transitional zone between the illuminated and the shadow regions broadens, together with a shadow boundary shift, as frequency decreases. With a scatterer of stress-free boundary condition, the shadow boundary shifts toward the illuminated region in both P- and SV-wave cases, with the amount of shift in the SV-wave case to be appreciably larger. These results have confirmed earlier observations in an ultrasonic model study. In contrast, with the same boundary condition, the SH-wave shadow boundary shifts toward the shadow region instead, with large SH amplitudes extending deep into the shadow zone. Implications of these findings are discussed with reference to the amplitudes of teleseismic body waves and the definition and location of the seismic shadow boundary.

Teng, Ta-liang, and Paul G. Richards, "Diffracted SH and SV," Nature, 218, 5147, 1154-1155, 1968.

Cleary et al (1967) have reported a number of diffracted S waves observed at distances from  $99^\circ$  to  $128^\circ$ . The most striking feature of their observations, as shown in their Fig. 1, is the great amplitude contrasts of the diffracted SV and SH waves. While Cleary et al. have explained their observations in terms of the faulting orientation there is a possible alternative explanation based on the results of several recent investigations.

In an ultrasonic model experiment intended to study the diffraction patterns of P and SV waves produced by a cylindrical cavity, it was found that at a finite frequency the shadow boundary (defined to be

the point at which diffracted amplitudes drop to half their original value) shifts away from the geometrical shadow boundary into the illuminated region. The amount of shift was found to be appreciably larger for SV waves than for P waves. In terms of observational seismology, this would suggest a possible early disappearance of SV waves in contrast to P waves at teleseismic distances. Parallel theoretical analyses have substantiated these findings, and have further shown that in contrast, at a finite frequency, the shadow boundary for SH waves shifts instead into the shadow zone.

Titles of papers presented at meetings:

McGinley, John R., Jr., "Effects of Lateral Inhomogeneities on the Earth's Free Oscillations," presented at the 64<sup>th</sup> Annual meeting of the Seismological Society of America at Tucson, Arizona, April 11-13, 1968.

Richards, Paul G., "Body Waves in a Radially Heterogeneous Earth," Trans. Am. Geophys. U., 49, 4, p. 716, December 1968.

Teng, T. L., and P. G. Richards, "Frequency Shift of P and S Shadow Boundaries," Trans. Am. Geophys. U., 49, 1, March 1968.

Johnson, Lane, "Some Unexplained Phases on the Seismograms of Deep-Focus Earthquakes," presented at the 64<sup>th</sup> Annual meeting of the Seismological Society of America at Tucson, Arizona, April 11-13, 1968.



#### IV. Theoretical and Observational Studies of Seismic Sources

There are three areas in which intense investigations of source connected phenomena are being conducted. First, purely theoretical studies designed to obtain realistic mathematical models of tectonic sources have been carried on. Both relaxation sources, which model an earthquake in terms of an initial value problem or equivalently as a growing boundary in a prestressed medium, and dislocation sources have evolved which, in appropriate limits, seem to approximate an earthquake very well. The range of applicability of the relaxation model seems very wide and has the flexibility required to model either fracture or phase change phenomena in (nonhydrostatically) prestressed media. The dislocation model has been shown to be equivalent to a relaxation model in the static limit. Both models can be used in the prediction of the radiation field from earthquakes. The relaxation source predicts both the time-space variation while the dislocation model requires an assumption of the equivalent source time function in order to provide the field time dependence as well as its spatial variation. On the other hand the dislocation model is, for long-period radiation, at least easier to apply computationally in the interpretation of data in terms of source parameters. Both models have, however, been successfully compared to field radiation data and have been used to determine source parameters. The relaxation model gives the prestress of the medium directly while both give the rupture velocity and dimensions and off set displacement along the fault.

Specialization of the general relaxation source theory to shock induced rupture in a prestressed medium has also been successful in the prediction of the anomalous radiation from nuclear explosions. For the class of explosions for which the anomalous field contains energy which is of the order of or less than the energy associated with the seismic field due to the converted shock wave, we conclude that this anomaly arises from the relaxation of stress in the region surrounding the shatter zone created by the explosion. Application of dynamical relaxation theory therefore enables us to obtain estimates of the prestress in the region. We have used this approach to estimate the prestress level at the Nevada Test Site, obtaining a stress of approximately 70 bars.

Applications of the dislocation models have been made to a large number of western U.S. earthquakes to determine seismic moment, source dimensions, and stress drops, associated with small earthquakes. These results are extremely useful in classifying earthquakes in terms of energy or magnitude versus rupture length; this classification being important to the identification of small events as earthquakes. In addition, the estimates of stress drop are important in determining the processes of rupture and hence an eventual detailed understanding of earthquake processes.

A second area of investigation has, therefore, been the observational work connected with the verification of source models and determination of source radiation field properties in general. Very extensive investigations of the radiation patterns as a function of frequency from both earthquakes and explosions have been carried on. This data provides us with a much more precise definition of source field properties for a wide class of sources. Coupled with precise knowledge of the medium from the work discussed earlier, we have been able to determine the radiation patterns from the source region itself, that is, the radiation field corrected for propagational effects. This data have been used as a check on theoretical source models and in related studies to determine source properties.

A third area of research has involved measurement and theoretical model calculations of the static strain and tilts due to earthquakes. Dislocation sources in various kinds of geometrical relationships to a medium containing weak zones (low rigidity layers) have been used in attempts to fit the rather unusual observations. One possible interpretation of the results of this study is that the southern California region responds to static field changes associated with earthquakes as if the region were composed of a rather large number of blocks of crustal material connected by relatively weak zones which were capable of easy flow or creep under static forcing conditions. In this case we can get calculated results which agree with the observations of normal strain and very large tilts. This work is very important in terms of its capability of shedding light on the manner in which the earth responds to static effects and how it may actually amplify the effects of an earthquake. In addition, we obtain very suggestive information related to continental tectonics.

#### Abstracts of Papers Submitted for Publication:

Archambeau, Charles, and Charles Sammis, "Seismic Radiation from Explosions in Prestressed Media and the Measurement of Tectonic Stress in the Earth," Rev. Geophys. (in press).

Theoretical predictions of the radiation field from explosions in a prestressed medium may be made on the basis of a dynamical theory of stress relaxation in the vicinity of the shock induced fracture zone created by an explosion. In this case the field consists of the normal compressional wave field resulting from the conversion of the shock wave to an elastic wave plus an anomalous part due to the release of strain energy. In this study we consider the nature of the radiation field to be expected from such a source in an inhomogeneous earth and determine the stress field required to explain the observations from a large underground explosion. The field is described in terms of radiation patterns as functions of frequency or alternately as the amplitude and phase spectrums at particular distances. These theoretical predictions are compared to

the Love and Rayleigh wave radiation patterns and spectra from the nuclear explosion Bilby. Using the known source parameters we obtain agreement between the observed radiation patterns and the predicted patterns for a pure shear prestress field equivalent to a shear couple oriented approximately N 10° W. Using the amplitude spectrum of the observed field adjusted for propagational effects we find that the prestress was  $70 \pm 20$  bars in the source area. We conclude that this approach can be utilized as a means of systematically measuring the stress field of the earth.

McGinley, John R., Jr., "A Comparison of Observed Permanent Tilts and Strains due to Earthquakes with those Calculated from Displacement Dislocations in Elastic Earth Models, Ph.D. Thesis, California Institute of Technology, Pasadena, 1969.

Theoretical solutions are derived for a model of faulting in elastic media and for the effect of lateral inhomogeneities on the earth's free oscillations. The solutions are used in a study of permanent tilts and strains observed a few hundred kilometers from earthquakes..

It is shown that the static deformational field due to a suitably chosen dislocation fault model is the same as that due to introduction of a stress free surface into a prestressed medium. Formal mathematical solutions are derived for the static deformational fields due to dislocation fault models in a homogeneous elastic sphere and a layered elastic half-space. For the layered half-space explicit solutions are given in terms of integral transforms for the surface displacements, tilts, and strains due to a slip fault and a dilatational source.

Numerical evaluation of the static, elastic, dislocation solutions shows that the observed tilts and strains are large compared with theoretical predictions and sometimes show the opposite sign. The hypothesis that a weak layer in the lower crust or upper mantle can explain the observations is investigated. It is found that a very weak layer, approaching a liquid-like behavior, does help to explain the observations. The compatibility of a very weak layer with observed surface wave dispersion is tested using the results of the perturbation calculations for the torsional free oscillations. A very weak layer is determined as compatible with observed surface wave dispersion only if very thin and with some frequency dependence in its elastic properties. It is concluded that although a regional weak layer in the lower crust or upper mantle can help to explain the observed tilts and strains, other regional or local structural effects or source complications must also be important.

Wyss, Max and James N. Brune, "Seismic Moment, Stress, and Source Dimensions for Earthquakes in the California-Nevada Region," J. Geophys. Res., 73, 14, 4681-6494, 1968.

The source mechanism of earthquakes in the California-Nevada region was studied using surface wave analyses, surface displacement observations in the source region, magnitude determinations, and accurate epicenter locations. Fourier analyses of surface waves from thirteen earthquakes in the Parkfield region have yielded the following relationship between seismic moment,  $M_0$  and Richter magnitude,  $M_L$ :  $\log M_0 = 1.4 M_L + 17.0$ , where  $3 < M_L < 6$ . The following relation between the surface wave envelope parameter AR and seismic moment was obtained:  $\log M_0 = \log AR_{300} + 20.1$ . This relation was used to estimate the seismic moment of 259 additional earthquakes in the western United States. The combined data yield the following relationship between moment and local magnitude:  $\log M_0 = 1.7 M_L + 15.1$ , where  $3 < M_L < 6$ . These data together with the Gutenberg-Richter energy-magnitude formula suggest that the average stress multiplied by the seismic efficiency is about 7 bars for small earthquakes at Parkfield and in the Imperial Valley, about 30 bars for small earthquakes near Wheeler Ridge on the White Wolf fault, and over 100 bars for small earthquakes in the Arizona-Nevada and Laguna Salada (Baja California) regions. Field observations of displacement associated with eight Parkfield shocks, along with estimates of fault area, indicate that fault dimensions similar to the values found earlier for the Imperial earthquake are the rule rather than the exception for small earthquakes along the San Andreas fault. Stress drops appear to be about 10% of the average stress multiplied by the seismic efficiency. The revised curve for the moment versus magnitude further emphasizes that small earthquakes are not important in strain release and indicate that the zone of shear may be about 6 km in vertical extent for the Imperial Valley and even less for oceanic transform faults.

Titles of papers presented at meetings:

Archambeau, C., and C. Sammis, "Seismic Radiation from Explosions in Prestressed Media," presented at the 64th Annual meeting of the Seismological Society of America at Tucson, Arizona, April 11-13, 1968.

Brune, James N., "Seismic Moment, Seismicity, and Rate of Slip Along Major Fault Zones," presented at the 64th Annual meeting of the Seismological Society of America at Tucson, Arizona, April 11-13, 1968.

Lambert, D. G., E. A. Flinn, and C. B. Archambeau, "Analysis of Surface-Wave Radiation Patterns for the Determination of Source Mechanisms," Trans. Am. Geophys. U., 49, 1, March 1968.

Smith, S. W., "Earthquake Strain Release," presented at the 64<sup>th</sup> Annual meeting of the Seismological Society of America at Tucson, Arizona, April 11-13, 1968.

Teng, Ta-Liang and Francis T. Wu, "A Two-Dimensional Ultrasonic Model of P- and S- Wave Diffraction Patterns and Frequency Shifts of Shadow Boundaries," presented at the 64<sup>th</sup> Annual meeting of the Seismological Society of America at Tucson, Arizona, April 11-13, 1968.

Wu, Francis T., "Source Mechanisms of Taiwan Earthquakes," presented at the 64<sup>th</sup> Annual meeting of the Seismological Society of America at Tucson, Arizona, April 11-13, 1968.

Wyss, M., and J. N. Brune, "Seismic Moment and Stresses for Earthquakes in the California-Nevada Region," presented at the 64<sup>th</sup> Annual meeting of the Seismological Society of America at Tucson, Arizona, April 11-13, 1968.

## V. Instrumental Development and Automated Data Processing

General instrumental development and improvement continued during the past year and was responsible in large part for the success of several of the observational studies carried on in other research areas. In addition, the ultra-long-period vertical seismometer at Isabella has been reworked in preparation for a study of ground and system noise in the period range 60-3000 seconds. The mechanical centering system has been significantly improved by the addition of a simple remotely adjustable mass on the boom. Centering the instrument after the tank has been evacuated is now much more effective.

In view of the continuance of study into the possible effects of large explosions on earthquake activity, it was determined that a strain gage with the capability of measuring earth strain changes of  $10^{-9}$  was required within 50 km of the site of a large underground explosion to collect appropriate data. Further work in this area will be funded by the AEC.

A program for the new IBM 360 system is being assembled to provide us with a programming system for our Ambilog Computer. We will use the IBM assembler to generate relocatable programs on magnetic tape in the symbolic Ambilog language. This will give us considerable flexibility in the use of the Ambilog computer in automated data processing. In addition, a wide variety of programs have been generated for the IBM 7094 and 360 systems. Some of these are general purpose programs suitable for processing large quantities of geophysical data. A time series analysis program package designed to filter, detrend, decimate, etc., time series, and compute spectra, phase and group velocities of the signal portion as well as to determine instrument response and apply appropriate corrections, is now available and can be obtained on request. Coupled with various inversion programs, we have an extensively automated system for analyzing geophysical data.

### Titles of Papers Presented at Meetings:

Smith, Stewart W., "Instrumental Techniques for Measuring Crustal Movement," Trans. Am. Geophys. U., 49, 4, December 1968.

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